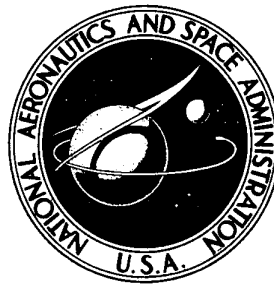


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**VERIFICATION OF TAKEOFF  
PERFORMANCE PREDICTIONS  
FOR THE XB-70 AIRPLANE**

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16. Abstract  <p style="text-align: center;">XB-70 airplane standardized takeoff data are compared with simple predictions based on aerodynamic and engine estimates. Effects of atmospheric and aircraft variables on takeoff distance are evaluated. Although experimentation with various techniques for aircraft rotation to lift-off attitudes was limited, the effect of the pilot techniques used are discussed and compared.</p> <p style="text-align: center;">Predictions of distance from brake release to initiation of rotation as a function of velocity were found to be accurate to approximately 100 feet (30 meters). Because of the significant drag at the high aircraft attitudes required for takeoff, the standardized ground roll distance for a given velocity was increased nominally by 400 feet (120 meters) over the distance which would occur with no increase in drag. Standardized performance during climb from lift-off to a height of 35 feet (10.7 meters) with all engines operating was marginal because of low longitudinal accelerations, resulting from high induced drag at lift-off attitude. Additional work is required to include rotation variables in standardizing test data and in more fully defining the rotation effects on performance from a limited number of takeoff tests.</p>					
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VERIFICATION OF TAKEOFF PERFORMANCE PREDICTIONS FOR THE  
XB-70 AIRPLANE

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INTRODUCTION

Considerable effort has been expended in the last few years in predicting the take-off characteristics of large aircraft and, in particular, large supersonic-cruise aircraft such as the supersonic transport (refs. 1 to 4). Particular characteristics of interest include heavy takeoff weights, low-aspect-ratio wings, slender, flexible fuselages with relatively high pitch and yaw moments of inertias, and moderately high thrust-to-weight ratios. The flight research program with the XB-70 airplane provided means for obtaining actual full-scale takeoff performance data on an airplane in this category.

This paper presents standardized takeoff performance data for the XB-70 airplane and compares these data with simple predictions based on aerodynamic and engine estimates. Included are the effects of atmospheric variation and other pertinent variables on XB-70 takeoff performance. Although experimentation with various techniques for rotating the aircraft to lift-off attitudes was limited, the effect of the pilot techniques used are discussed and compared.

The data presented in this paper were obtained from takeoffs of the XB-70 airplane during a flight program conducted jointly at Edwards Air Force Base, Calif., by the U. S. Air Force, North American Rockwell Corp., and the NASA Flight Research Center.

SYMBOLS

The units used for physical quantities in this paper are given in U. S. Customary Units and parenthetically in the International System of Units (SI).

$a_n$	normal acceleration, g
$a_x$	aircraft acceleration tangent to runway, ft/sec <sup>2</sup> (m/sec <sup>2</sup> )
$\overline{a_{xCL}}$	average longitudinal acceleration for constant lift coefficient during ground roll, ft/sec <sup>2</sup> (m/sec <sup>2</sup> )
$C_D$	drag coefficient

$C_L$	aerodynamic lift coefficient
$C_{L_{LOF_s}}$	standardized lift coefficient for lift-off (eq. (A3))
$D$	drag, lb (N)
$F$	thrust of aircraft, lb (N)
$F_g$	gross thrust of aircraft, lb (N)
$F_n$	net thrust of aircraft, lb (N)
$f$	frequency of occurrence
$g$	acceleration due to gravity, ft/sec <sup>2</sup> (m/sec <sup>2</sup> )
$h$	height above runway, ft (m)
$h_a$	air-phase height, 35 ft (10.7 m) above lift-off point
$h_p$	pressure altitude, ft (m)
$h_v$	specific kinetic-energy increase of aircraft gained during air phase, $\frac{(V_a)^2 - (V_{LOF})^2}{2g}, \text{ ft (m)}$
$L$	lift, lb (N)
$S$	wing area, ft <sup>2</sup> (m <sup>2</sup> )
$S_a$	horizontal distance traveled by aircraft from lift-off to air-phase height of 35 ft (10.7 m), ft (m)
$S_g$	ground roll distance (distance traveled by aircraft from brake release to lift-off), ft (m)
$S_{gC_L}$	ground roll distance corrected to a constant $C_L$ at lift-off, ft (m)
$S_{gc}$	ground roll distance corrected to a condition of zero wind, zero runway slope, and constant lift coefficient at lift-off, ft (m)
$S_{gs(V)}$	ground roll distance standardized for relating distance to aircraft velocity, ft (m)
$S_{gs(W)}$	ground roll distance standardized for relating distance to aircraft weight, ft (m)

$S_{gw}$	ground roll test distance referenced to zero wind, ft (m)
$S_{rs}(V)$	ground roll distance traveled by aircraft from brake release to initiation of rotation, standardized for relating distance to aircraft velocity, ft (m)
$S_0$	horizontal distance from brake release, ft (m)
$T$	ambient temperature, °F (°C)
$t$	time, sec
$t_a$	time at air-phase height, sec
$V$	aircraft velocity, knots
$V_a$	aircraft velocity at air-phase height, knots
$V_i$	indicated velocity, knots
$V_{i_a}$	indicated velocity at air-phase height, knots
$V_{LOF_{C_{L_S}}}$	aircraft lift-off velocity standardized to a constant lift coefficient (eq. (A3)), knots
$V_w$	wind velocity, knots
$W$	aircraft weight, lb (kg)
$\alpha$	aircraft angle of attack, deg
$\Delta$	algebraic change in value of reference variable
$\delta_e$	average elevon deflection of aircraft, deg
$\theta$	aircraft pitch attitude, deg
$\mu$	coefficient of rolling friction
$\rho$	ambient density, slugs/ft <sup>3</sup> (kg/m <sup>3</sup> )
$\sigma$	ratio of measured ambient density to standard value
Subscripts:	
LOF	lift-off of aircraft
r	initiation of rotation

s                    standardized value  
t                    test value

A bar over a quantity denotes the average value of that quantity.

### AIRPLANE DESCRIPTION

The XB-70 airplane (fig. 1) was a delta-wing airplane designed for long-range supersonic cruise. Its maximum gross weight exceeded 500,000 pounds (227,000 kilograms). Of the two XB-70 airplanes built, the only significant difference in configuration was in the wing dihedral; the first airplane (XB-70-1) had  $0^\circ$  dihedral, and the second airplane (XB-70-2) had  $5^\circ$  dihedral. Specific configuration details are included in reference 5.

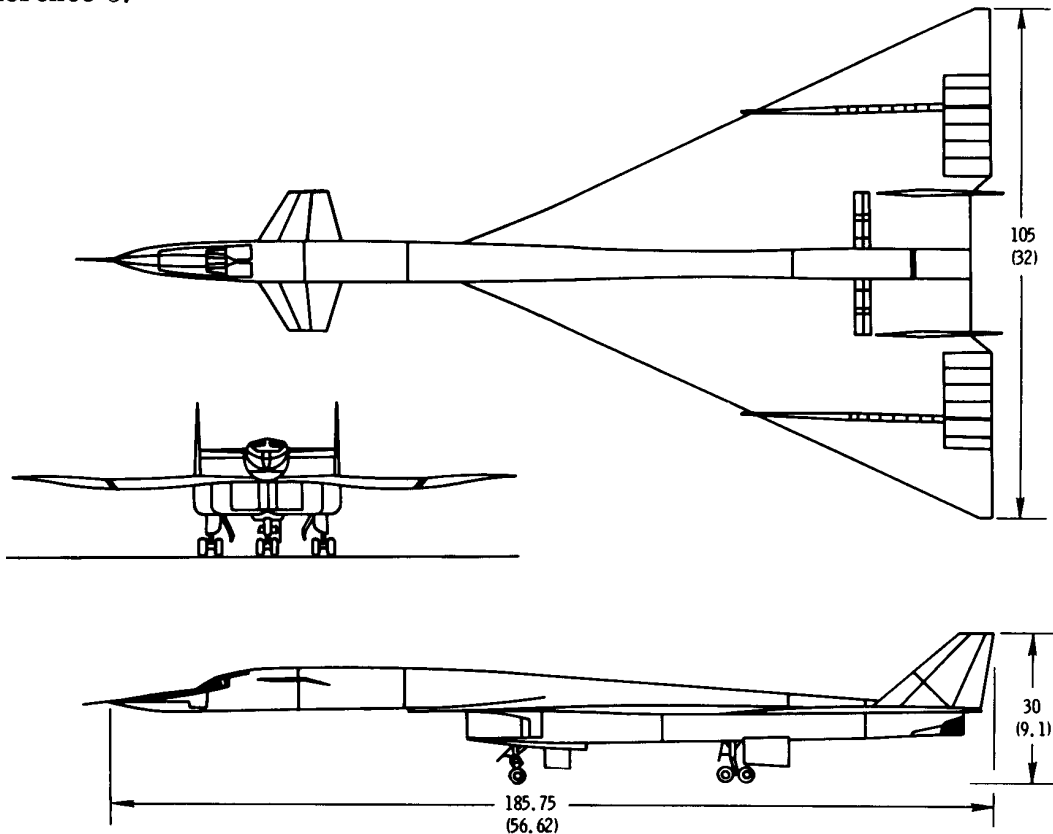


Figure 1. Three-view drawing of the XB-70 airplane. Dimensions in feet (meters).

Each aircraft had a canard surface and segmented trailing-edge elevons, with six segments to a side. During takeoff and landing, canard incidence was set at  $0^\circ$ , and the canard flaps were deflected to the  $20^\circ$  position. The foldable wing tips were undeflected during takeoff and landing.

The airplane's propulsion system consisted of six YJ93-GE-3 engines with sea-level, static-thrust ratings of approximately 30,000 pounds (130,000 newtons).

The landing gear was a conventional tricycle arrangement with four wheels on each main gear and two on the nose gear. A detailed description of the landing gear is presented in reference 6.

Wing loading varied from 68 lb/ft<sup>2</sup> to 85 lb/ft<sup>2</sup> (332 kg/m<sup>2</sup> to 415 kg/m<sup>2</sup>). The center of gravity varied from 20.8 percent to 24.5 percent of the mean aerodynamic chord. The maximum trailing-edge-up elevon deflection used for rotation was 12° of the 20° or 25° available.

## TEST PROCEDURES

Takeoffs were made in both directions from the main, 15,000-foot (4600-meter), concrete runway at Edwards Air Force Base, Calif. This runway has a mean elevation of 2291 feet (698.3 meters) and a grade of 0.14 percent. Dry runway conditions prevailed during all the tests. No abnormal takeoff tests, such as abused takeoffs, were made.

In the normal takeoff procedure the six engines were set to minimum afterburner power before brake release. The brakes were then released, the throttles were advanced to maximum afterburner power (usually within 10 seconds or less from brake release), and the airplane was allowed to accelerate to a nominal speed of 20 knots below the intended lift-off speed as determined from the pilot's aircraft manual. The airplane was rotated by elevon control to about 10° pitch attitude, which the pilot established by sighting the upper surface of the fuselage nose on the horizon. This attitude was held until lift-off.

Although little experimentation with XB-70 takeoff was accomplished, a few of the rotations were initiated at a speed approximately 30 knots lower than the intended lift-off speed. Also, significant variations in rotation procedures occurred because of pilot technique.

## MEASUREMENTS AND ANALYSIS

Data were obtained from three sources: space-positioning data from an Askania cinetheodolite tracking system (ref. 7), meteorological information from the Air Weather Service at Edwards Air Force Base, and the remainder of the data from the XB-70 onboard recording system (ref. 5). Velocity and acceleration were calculated from the space-positioning data. For the 4-frame-per-second tracking data, two-station solutions and a seven-point smoothing procedure were used.

The primary parameters recorded by the XB-70 data system and used in the analysis in this report included angle of attack, elevon position, pressure altitude, indicated airspeed, and fuel quantity (for weight determination). Angle of attack was measured by a vane mounted on the nose boom of the airplane.

The estimated accuracies of all the pertinent quantities used in evaluating takeoff performance are presented in the tabulation on the next page.

<u>Quantity</u>	<u>Accuracy</u>
Position	$\pm 2$ ft ( $\pm 0.6$ m)
Velocity	$\pm 1$ knot
Acceleration	$\pm 0.1$ ft/sec <sup>2</sup> ( $\pm 0.03$ m/sec <sup>2</sup> )
Angle of attack	$\pm 0.5^\circ$
Elevon position	$\pm 1^\circ$
Thrust	$\pm 5000$ lb ( $\pm 22,000$ N)
Weight	$\pm 500$ lb ( $\pm 230$ kg)
Temperature	$\pm 1^\circ$ F ( $\pm 0.6^\circ$ C)
Pressure	$\pm 2$ lb/ft <sup>2</sup> ( $\pm 100$ N/m <sup>2</sup> )

Evaluation of takeoff performance requires that the data for each takeoff be corrected to standard conditions. Therefore, the data were corrected to sea-level, standard-day, no wind conditions for standard weights and lift coefficients. Procedures for making these corrections are described in appendix A. Table 1 presents the test and standardized values of takeoff distances and velocities, as well as pertinent quantities used to standardize each takeoff analyzed.

Ground roll performance was evaluated at the initiation of rotation (lift-off of the nosewheel) and at the lift-off of the last wheel to become airborne. Distance values were referenced from brake release. Air-phase performance was evaluated at the time the aft bogie was 35 feet (10.7 meters) above the takeoff point. Distances were projected from lift-off directed along the runway.

## RESULTS AND DISCUSSION

### General Takeoff Characteristics

Time histories of two XB-70 takeoffs are shown in figure 2. Figure 2(a) is representative of the normal takeoff procedure in which the pilot initiated rotation approximately 20 knots lower than the intended lift-off speed. Figure 2(b) is representative of the few takeoffs in which rotation was initiated approximately 30 knots lower than the intended lift-off speed. From these figures, it can be seen that the longitudinal acceleration increased to near its maximum value during the first 10 seconds, as the pilot advanced all engines to maximum afterburner, and remained essentially constant after this time until the initiation of rotation. During rotation, the acceleration decreased markedly. This reduction resulted mainly from the large increase in drag due to lift associated with the nose-high attitude of the airplane.

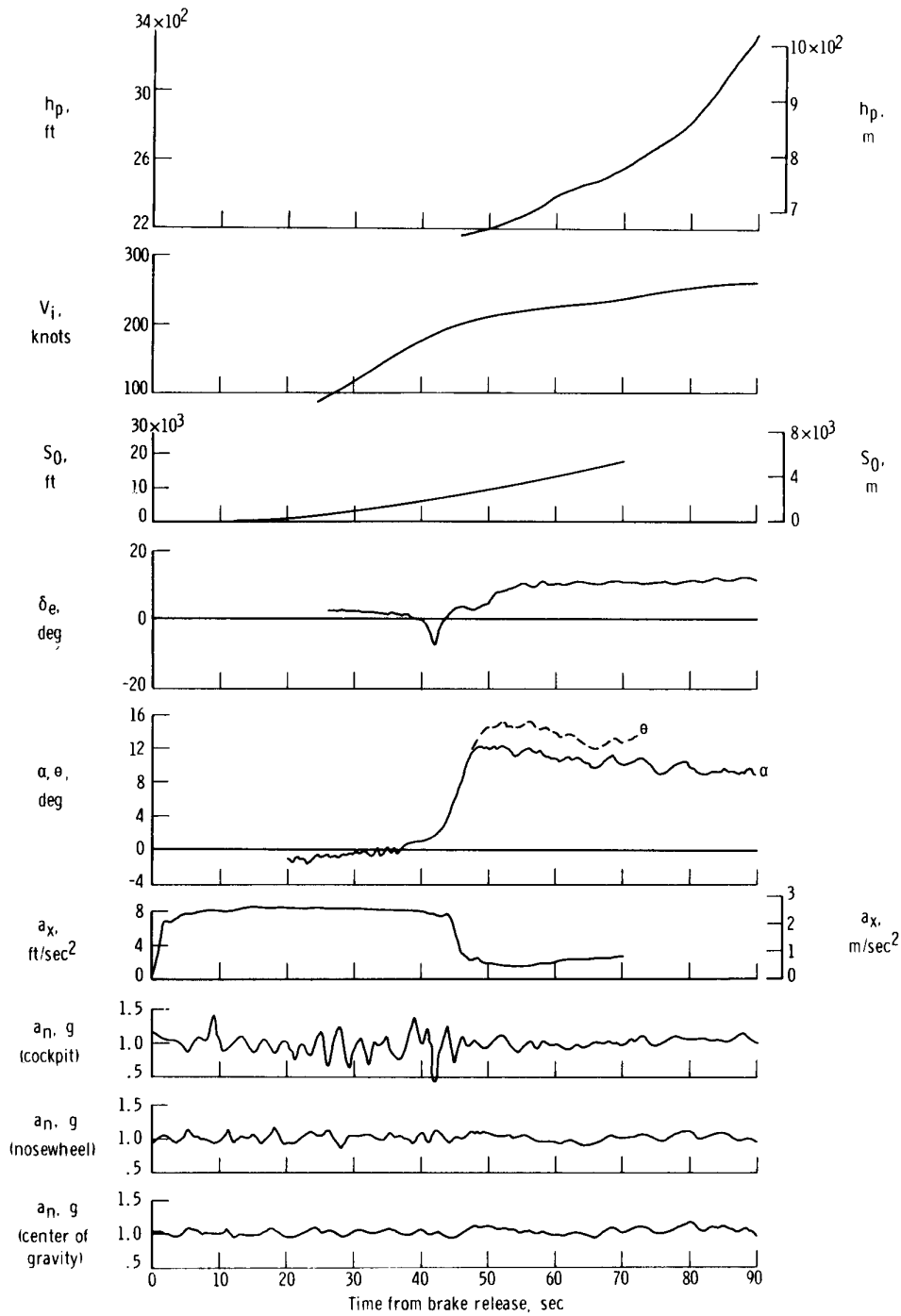
Marginal air-phase performance with all engines operating (from lift-off to 35 ft (10.7 m)) was indicated by the low values of longitudinal acceleration at lift-off. Because of the low excess thrust of the XB-70 airplane during the air phase, initial climb angles typically ranged from  $1^\circ$  to  $2^\circ$ . As a result, negative values of longitudinal acceleration sometimes occurred; an example is shown in figure 2(b) 78 seconds after brake release.

Although it was not specifically a problem in these tests, the extremely rough ride in the cockpit, as indicated by the normal-acceleration trace in figure 2(a), could cause some concern for the pilot's ability to perform the takeoff, especially for takeoffs from rough runways. Although the variation in vertical acceleration at the center of gravity



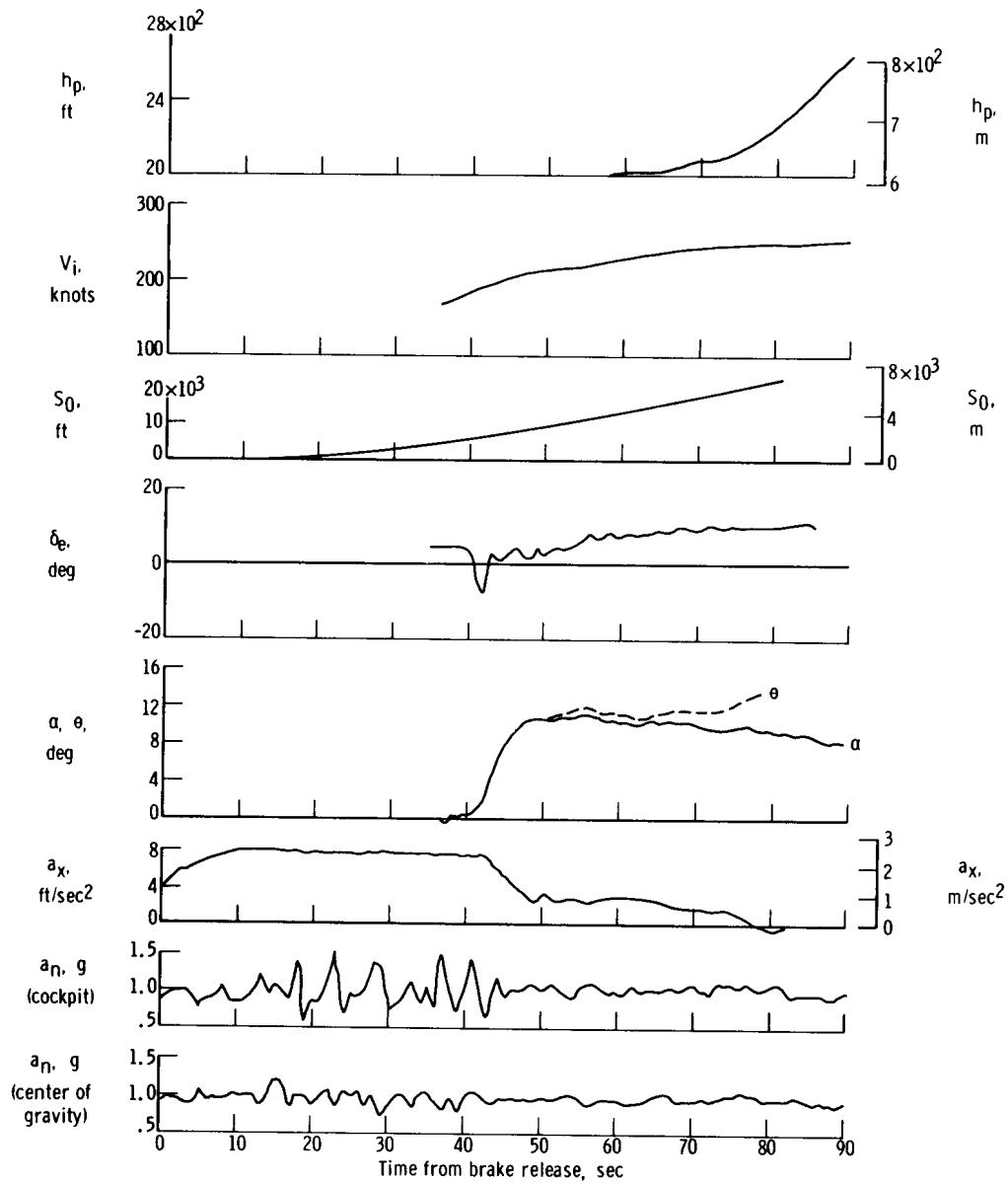
TABLE 1. - QUANTITIES FOR EVALUATION OF XB-70 TAKEOFF PERFORMANCE

Takeoff test conditions										Atmospheric conditions					Takeoff performance												
Flight	Takeoff heading, deg	Fg, Wt	Wt		Wt, kg	Ws, kg	T		Vw, knots	Wind direction, deg	Sgt		Scg		Sgs(W)		Sgs(V)		VLOFL, knots	VLOFS, knots	Sat		Sst		h, m	Vgt, knots	
			lb	kg			F	C			lt	m	lt	m	lt	m	lt	m			lt	m	lt	m			lt
1-2	222	0.345	106.1	184.2	184.2	184.2	49	9.4	0.861	01	360	6,780	2066.5	7,640	2328.7	3080	1548.4	5620	1713.0	200	192	1350	411.5	947	285.6	99	36.2
1-3	222	0.355	109.6	186.9	186.9	186.9	75	23.9	0.834	05	235	6,780	2066.5	7,420	2261.6	3680	1725.2	6000	1828.8	200	195	2000	609.6	1479	150.8	252	214
1-4	222	0.365	113.1	189.6	189.6	189.6	57	13.9	0.823	03	200	7,349	2540.0	7,000	2183.6	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-5	222	0.374	116.6	192.1	192.1	192.1	54	12.2	0.833	03	060	7,110	2185.4	7,000	2401.8	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-6	222	0.383	120.1	194.6	194.6	194.6	51	10.6	0.840	08	240	8,250	2508.9	7,800	2401.8	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-7	222	0.392	123.6	197.1	197.1	197.1	53	11.7	0.824	20	240	7,060	2540.0	7,800	2401.8	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-8	222	0.401	127.1	200.1	200.1	200.1	50	10.1	0.830	15	280	7,350	2435.4	8,820	2401.8	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-9	222	0.410	130.6	203.1	203.1	203.1	78	23.6	0.808	12	010	10,000	2490.9	8,820	2401.8	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-10	222	0.419	134.1	206.1	206.1	206.1	66	18.9	0.810	07	045	9,780	2497.4	8,820	2401.8	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-11	222	0.428	137.6	209.1	209.1	209.1	56	13.3	0.824	07	045	9,780	2497.4	8,460	2383.4	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-12	222	0.437	141.1	212.1	212.1	212.1	56	13.3	0.824	07	045	9,780	2497.4	8,460	2383.4	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-13	222	0.446	144.6	215.1	215.1	215.1	56	13.3	0.824	07	045	9,780	2497.4	8,460	2383.4	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-14	222	0.455	148.1	218.1	218.1	218.1	56	13.3	0.824	07	045	9,780	2497.4	8,460	2383.4	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-15	222	0.464	151.6	221.1	221.1	221.1	56	13.3	0.824	07	045	9,780	2497.4	8,460	2383.4	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-16	222	0.473	155.1	224.1	224.1	224.1	56	13.3	0.824	07	045	9,780	2497.4	8,460	2383.4	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-17	222	0.482	158.6	227.1	227.1	227.1	56	13.3	0.824	07	045	9,780	2497.4	8,460	2383.4	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-18	222	0.491	162.1	230.1	230.1	230.1	56	13.3	0.824	07	045	9,780	2497.4	8,460	2383.4	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-19	222	0.500	165.6	233.1	233.1	233.1	56	13.3	0.824	07	045	9,780	2497.4	8,460	2383.4	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-20	222	0.509	169.1	236.1	236.1	236.1	56	13.3	0.824	07	045	9,780	2497.4	8,460	2383.4	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-21	222	0.518	172.6	239.1	239.1	239.1	56	13.3	0.824	07	045	9,780	2497.4	8,460	2383.4	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-22	222	0.527	176.1	242.1	242.1	242.1	56	13.3	0.824	07	045	9,780	2497.4	8,460	2383.4	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-23	222	0.536	179.6	245.1	245.1	245.1	56	13.3	0.824	07	045	9,780	2497.4	8,460	2383.4	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-24	222	0.545	183.1	248.1	248.1	248.1	56	13.3	0.824	07	045	9,780	2497.4	8,460	2383.4	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-25	222	0.554	186.6	251.1	251.1	251.1	56	13.3	0.824	07	045	9,780	2497.4	8,460	2383.4	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-26	222	0.563	190.1	254.1	254.1	254.1	56	13.3	0.824	07	045	9,780	2497.4	8,460	2383.4	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-27	222	0.572	193.6	257.1	257.1	257.1	56	13.3	0.824	07	045	9,780	2497.4	8,460	2383.4	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-28	222	0.581	197.1	260.1	260.1	260.1	56	13.3	0.824	07	045	9,780	2497.4	8,460	2383.4	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-29	222	0.590	200.6	263.1	263.1	263.1	56	13.3	0.824	07	045	9,780	2497.4	8,460	2383.4	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-30	222	0.599	204.1	266.1	266.1	266.1	56	13.3	0.824	07	045	9,780	2497.4	8,460	2383.4	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-31	222	0.608	207.6	269.1	269.1	269.1	56	13.3	0.824	07	045	9,780	2497.4	8,460	2383.4	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-32	222	0.617	211.1	272.1	272.1	272.1	56	13.3	0.824	07	045	9,780	2497.4	8,460	2383.4	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-33	222	0.626	214.6	275.1	275.1	275.1	56	13.3	0.824	07	045	9,780	2497.4	8,460	2383.4	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-34	222	0.635	218.1	278.1	278.1	278.1	56	13.3	0.824	07	045	9,780	2497.4	8,460	2383.4	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-35	222	0.644	221.6	281.1	281.1	281.1	56	13.3	0.824	07	045	9,780	2497.4	8,460	2383.4	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-36	222	0.653	225.1	284.1	284.1	284.1	56	13.3	0.824	07	045	9,780	2497.4	8,460	2383.4	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-37	222	0.662	228.6	287.1	287.1	287.1	56	13.3	0.824	07	045	9,780	2497.4	8,460	2383.4	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-38	222	0.671	232.1	290.1	290.1	290.1	56	13.3	0.824	07	045	9,780	2497.4	8,460	2383.4	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-39	222	0.680	235.6	293.1	293.1	293.1	56	13.3	0.824	07	045	9,780	2497.4	8,460	2383.4	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-40	222	0.689	239.1	296.1	296.1	296.1	56	13.3	0.824	07	045	9,780	2497.4	8,460	2383.4	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-41	222	0.698	242.6	299.1	299.1	299.1	56	13.3	0.824	07	045	9,780	2497.4	8,460	2383.4	3790	1764.8	6590	2008.6	208	209	1870	570.0	1633	497.8	222	17.7
1-42	222	0.																									



(a) Rotation 20 knots prior to intended lift-off.  $t_r = 42.5$  sec;  $t_{LOF} = 47.5$  sec;  $t_a = 51.5$  sec;  $V_{i_r} = 187$  knots;  $V_{i_{LOF}} = 206$  knots;  $V_{i_a} = 215$  knots.

Figure 2. Time histories of two typical XB-70 takeoffs.



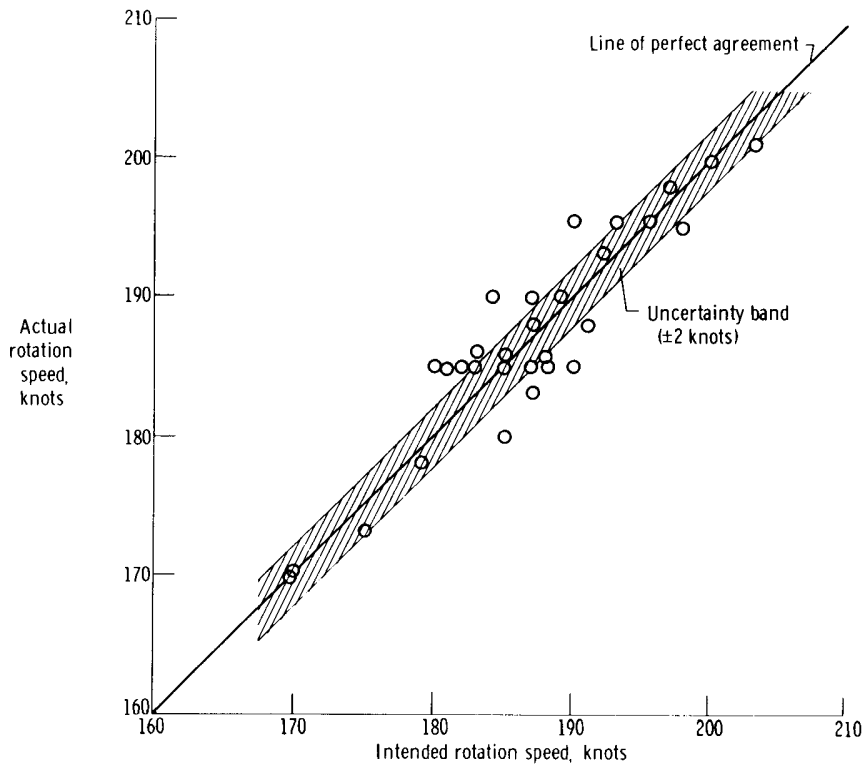
(b) Rotation 30 knots prior to intended lift-off.  $t_r = 41.0$  sec;  $t_{LOF} = 49.5$  sec;  $t_a = 58.5$  sec;  $V_{i_r} = 186$  knots;  $V_{i_{LOF}} = 212$  knots;  $V_{i_a} = 225$  knots.

Figure 2. Concluded.

is generally  $\pm 0.1g$ , the magnitude increases with distance forward of this location until, at the cockpit, the variation is nearly  $\pm 0.5g$ . Compared with the other locations shown, the cockpit acceleration trace tends to have sharper peaks, which are approximately  $180^\circ$  out of phase with similar traces for these other locations. In accordance with the pilots' observations, figure 2(a) shows that the normal accelerations significantly increase after a speed of approximately 90 knots is reached and then tend to decrease at higher speeds well before rotation. The data also show that the accelerations increase again near the time of rotation, but the pilots did not find them to be particularly objectionable at this point. Once the nose was raised to  $8^\circ$  attitude, where most of the

weight was off the main gear, the cockpit acceleration was comparable to the other accelerations.

Figure 3 substantiates the general opinion of the pilots that the rough ride of the XB-70 airplane did not materially affect their ability to initiate the rotation maneuver. The data were obtained from pilot reports on the intended versus the actual rotation speeds. When compared with the 45° line of perfect agreement, the speed differences are satisfactorily small. Considering the transient nature of these observations and the variety of cockpit instruments used during the test program, the accuracy of this information is within approximately 2 knots.



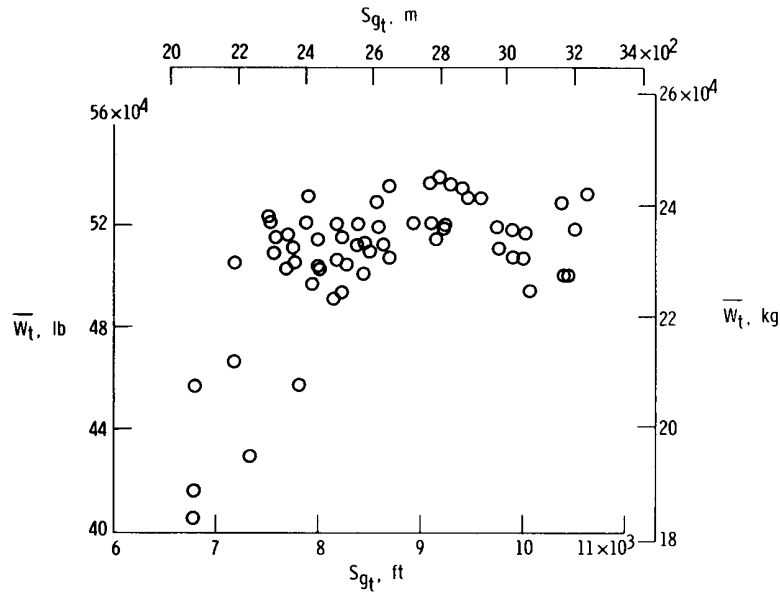
*Figure 3. Comparison of actual velocity at initiation of rotation with intended velocity.*

As discussed later, the variations in technique of rotating the aircraft (slow or fast, overrotations or underrotations) caused large differences in takeoff performance. The faster rotations, initiated 20 knots prior to intended lift-off, were favored by the pilots because it was easier to attain the desired lift-off conditions. For example, figure 2(b) shows that, when rotation was initiated 30 knots prior to intended lift-off, the desired takeoff attitude was attained approximately 2 seconds prior to lift-off. Figure 2(a) indicates that the takeoff attitude was attained coincidentally with lift-off when rotation was initiated 20 knots prior to intended lift-off.

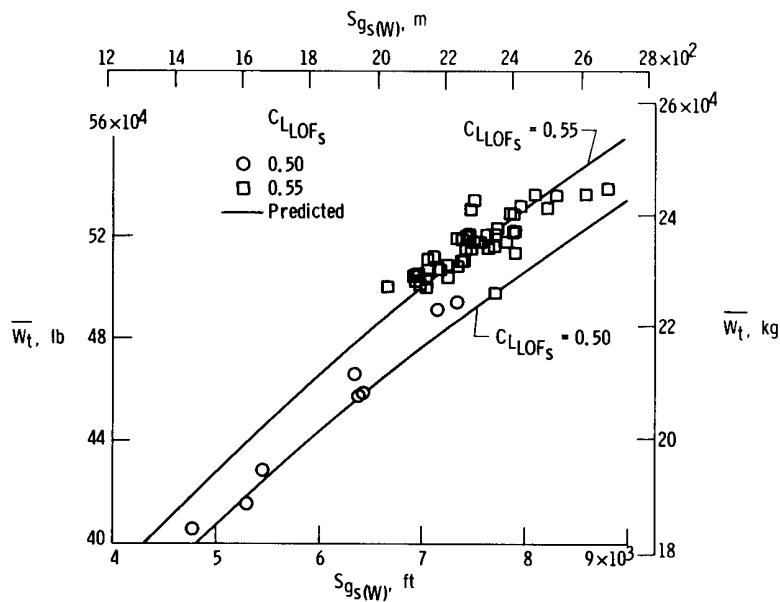
#### Predicted and Measured Ground Roll Performance

The takeoff performance of the XB-70 airplane was greatly affected by variations of atmospheric conditions, airplane weight, and pilot technique of rotating the airplane

prior to lift-off. The fact that weight alone was not the sole factor is reflected in figure 4(a), which presents the test ground roll distance to lift-off as a function of average aircraft weight during ground roll. Although all the takeoffs were from the same runway, a dispersion of about 3000 feet (900 meters) resulted for a typical weight of 520,000 pounds (236,000 kilograms). Figure 4(b) presents takeoff performance with



(a) Uncorrected data.



(b) Standardized data.

Figure 4. Variation of XB-70 ground roll distance at lift-off with average aircraft weight during ground roll.

the same data points shown in figure 4(a) but with distances corrected to zero wind, constant lift coefficient at lift-off, and standard thrust and air density. The predicted performance curves, to be discussed later, are based on the simplified calculation outlined in appendix B and on the lift, drag, and thrust curves of reference 8. The lighter weight takeoffs ( $< 500,000$  lb (227,000 kg)) were corrected to a  $CL_{LOF_S}$  of 0.50, and the data of the heavier weight takeoffs ( $W_t \geq 500,000$  lb (227,000 kg)) were corrected to a  $CL_{LOF_S}$  of 0.55.

The close correlation of the magnitudes and trends of the test data and predicted curves in figure 4(b) shows that the standardization procedures of appendix A effectively account for variations between test and standard conditions. Further verification of this is shown in figure 5, in which the variations of standardized velocity with standardized ground distance at rotation for several airplane weights are presented. The predicted curves (based on appendix B) indicate larger ground roll distances than shown by the test data. Other performance data on the XB-70 airplane indicate that the predicted thrust of reference 8 is approximately 3 percent low, which accounts for most of the 300- to 400-foot (90- to 120-meter) discrepancy in ground roll distance for a 520,000-pound (236,000-kilogram) airplane. Thus, it is concluded that the simple prediction techniques are adequate for determining distance as a function of velocity at initiation of rotation to an accuracy of about 100 feet (30 meters). The  $\pm 250$  feet ( $\pm 75$  meters) of scatter in the takeoff data at a given velocity is attributed to variations in pilot techniques in advancing the throttles to maximum afterburner during the initial ground roll and to slight inaccuracies in the test data and correction procedures used.

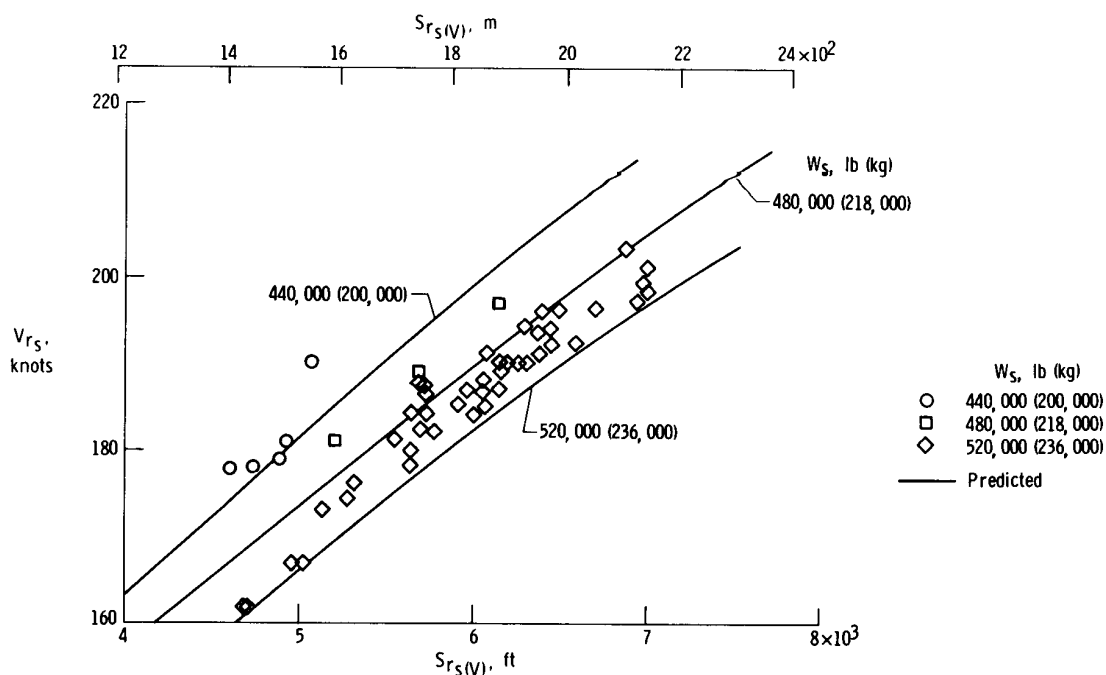


Figure 5. Variation of XB-70 ground roll distance at initiation of rotation with velocity.

Effects of rotation on ground roll performance.— Figure 6 shows the variation of velocity with standardized ground distance at lift-off for several airplane weights. The predicted curves from figure 5 are presented for reference. Although it appears that flight and predicted results agree, this is not a valid comparison because the predicted curves do not include the effects of rotation. Also, the predicted curve for 520,000 pounds (236,000 kilograms) would be as much as 400 feet (120 meters) shorter than indicated by the data if corrected for the deficiency in predicted thrust, as just discussed. This 400-foot (120-meter) difference is caused by the variations in drag due to lift during a nominal rotation and should be accounted for in the predictions. These effects of rotation become apparent when the flight results of figures 5 and 6 are compared. The apparent increase in scatter in figure 6 of approximately 300 feet (90 meters) at a given velocity over the scatter in figure 5 is caused by the variations in pilot technique in rotating the aircraft to the takeoff attitude. This too should be accounted for in more precise predictions.

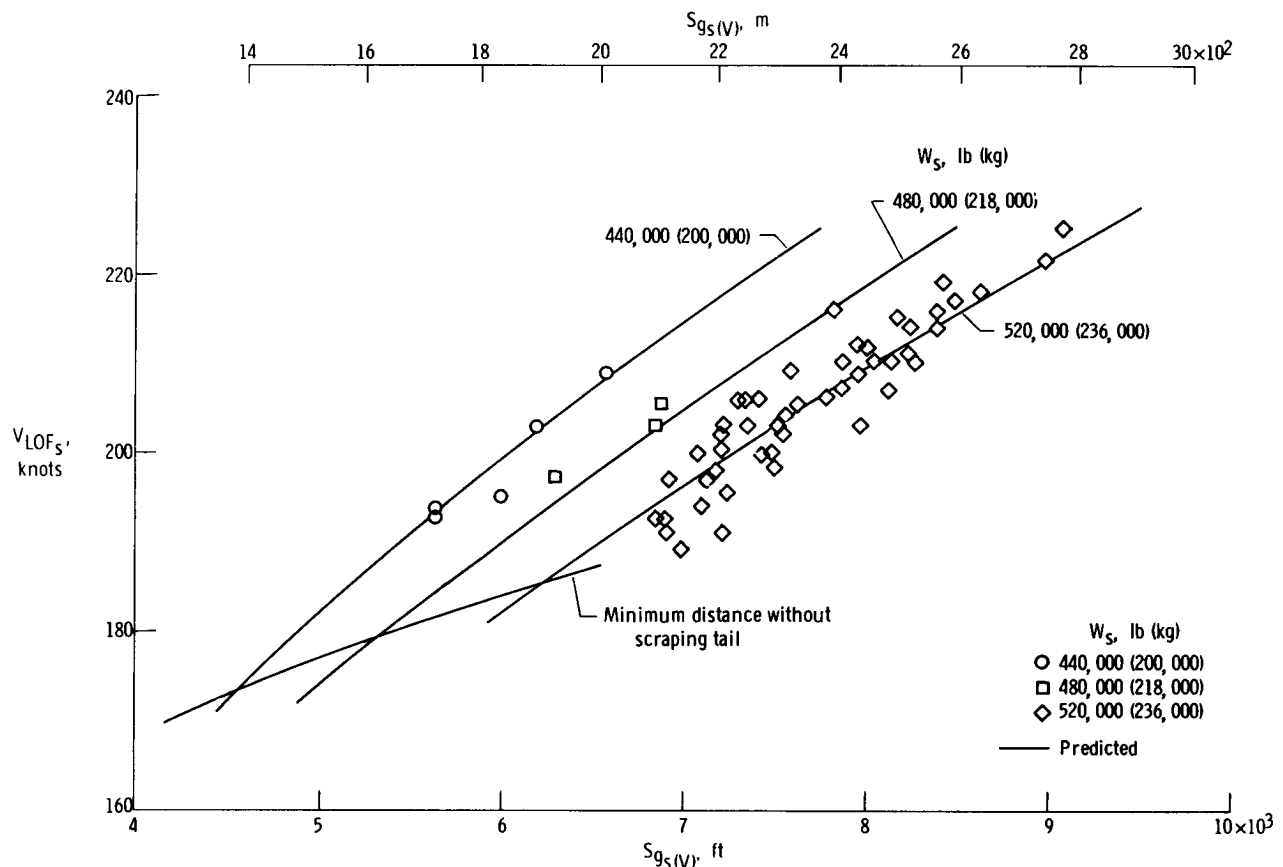


Figure 6. Variation of XB-70 ground roll distance at lift-off with velocity.

The complexity of predicting the effects on performance of all possible rotation techniques is illustrated in figure 7. This figure shows only one class of rotation, in which it is assumed that the pilot initiates the rotation at the intended speed and that he arrives at a designated steady-state attitude. Also shown are the predicted lift-off boundaries for takeoff and zero-acceleration boundaries for an airplane weight of

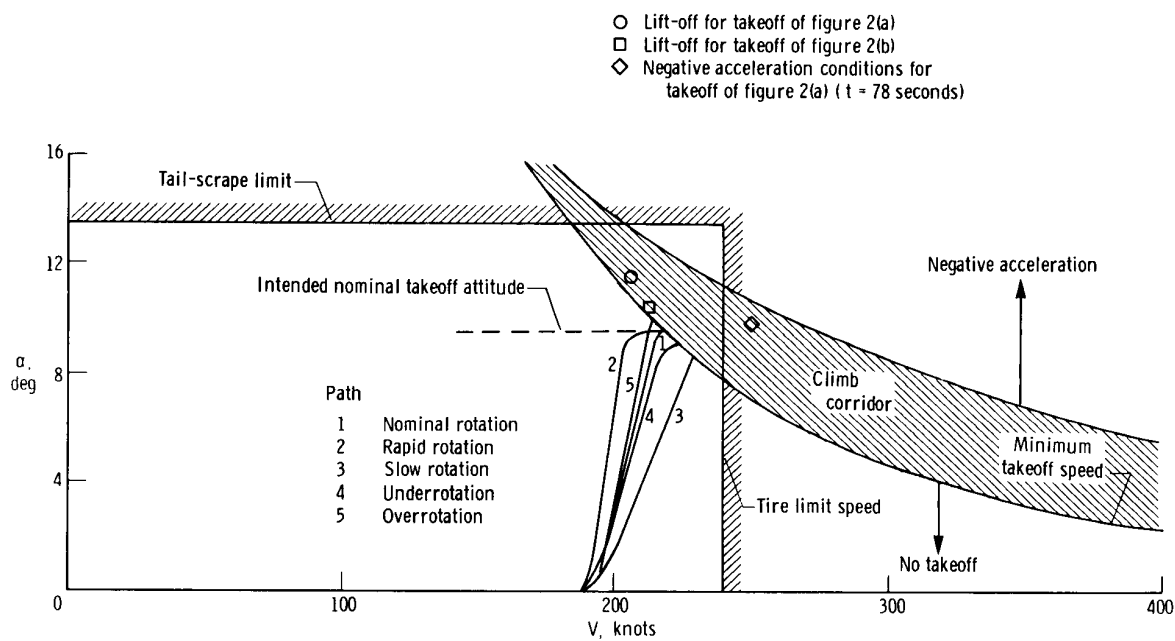


Figure 7. XB-70 envelope of angle of attack and velocity for takeoff.  $W = 520,000 \text{ lb (236,000 kg)}$ .

520,000 pounds (236,000 kilograms) (based on ref. 8). Data from the takeoff time histories (fig. 2) are also shown for reference. Only a general comparison is intended, because the curves are calculated for standard, sea-level conditions and the data points are actual test conditions.

Path 1 of figure 7 represents a nominal rotation for which the airplane arrives at the intended attitude at the proper velocity for takeoff. Path 2 indicates a rapid rotation in which the drag and distance penalty paid depends on how early the airplane reaches the takeoff attitude. Path 3 illustrates a slow rotation in which the airplane lifts off before the desired attitude is reached. The distance penalty lies in the time and distance it takes to accelerate to the higher speed. Path 4 represents an under-rotation with performance penalties similar to those for the slow rotation (path 3). Path 5 shows an overrotation which, when executed properly, can produce shorter ground roll; however, it places the airplane nearer the limits imposed by the tail-scape angle and the zero-acceleration boundary and minimum control speeds for engine-out conditions. When other types of rotation techniques are included, the matrix of conditions to be considered becomes very large.

To further illustrate the effects of rotation on XB-70 performance, figure 8 presents the velocity change during the rotation phase versus the corresponding time to rotate the aircraft. For takeoffs with intended rotation velocity increments of 20 knots, the actual increments varied from 9 knots lower to 2 knots higher than the intended 20 knots. For the takeoffs with intended increments of 30 knots, the actual values varied from 3 to 7 knots lower than desired. These results show that the actual velocity changes were generally less than intended. This dispersion resulted mainly from variations in the rotation profiles, such as those shown in figure 7. Note that the dispersion of rotation time is directly proportional to the nominal rotation times



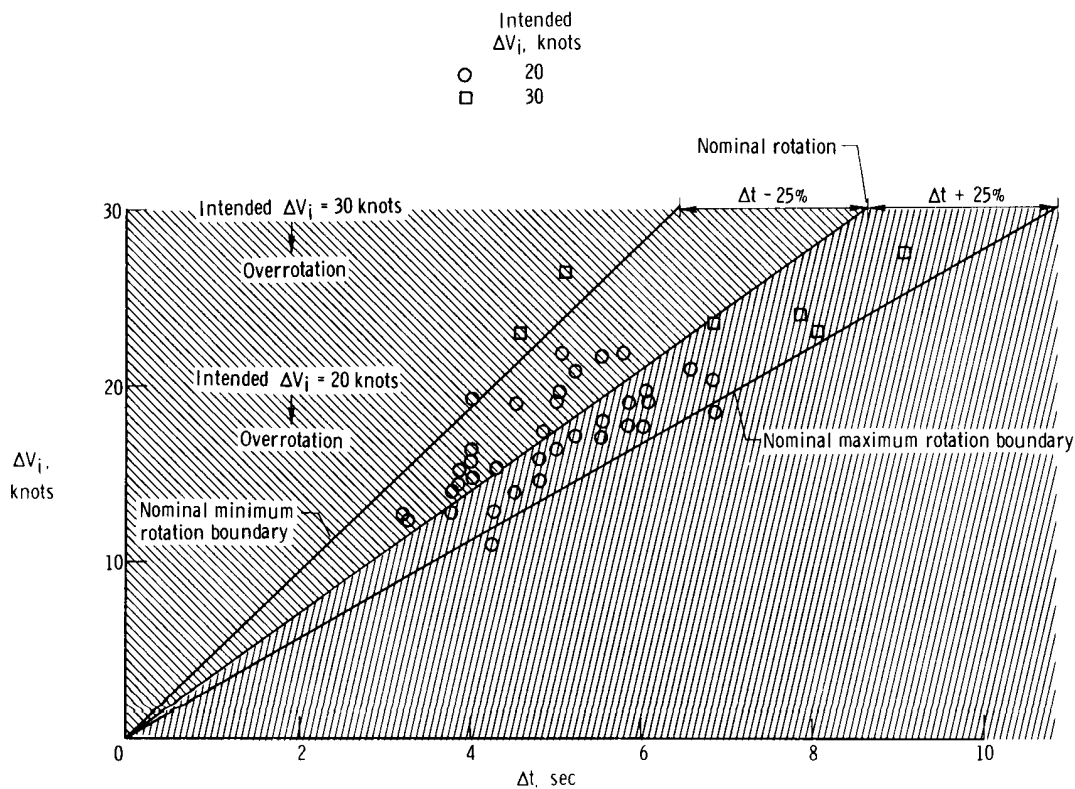


Figure 8. XB-70 incremental speed change during rotation as a function of rotation time.

and generally falls within 25 percent of the nominal. The large dispersion in rotation times for the intended 30-knot velocity increments represents a variation in takeoff distance of 1500 feet (460 meters).

Also, as indicated in figure 8, rotations covering less than the planned velocity increment tend toward an overrotation condition, because a higher takeoff attitude generally results. This tendency toward overrotation was not considered to be a problem for the XB-70 airplane when rotations were initiated 20 knots prior to lift-off; however, rotations initiated 30 knots prior to lift-off usually resulted in early arrival at the takeoff attitude, overrotation, or both.

From this discussion, it is evident that pilot techniques of rotating the XB-70 airplane had significant effects on the takeoff performance. Further, these effects were not accounted for in the conventional means of standardizing takeoff data or in predicting the takeoff performance of the XB-70 airplane. The effect of varying rotation techniques on takeoff performance can be analyzed. (See, for example, reference 1.) However, more work is required to include rotation variables in standardizing test data and in more fully defining the rotation effects on performance from a limited number of takeoff tests.

Effects of other variables on ground roll performance. — The effects of individual parameters such as temperature, pressure, density, wind, runway slope, and friction on ground roll distance were evaluated by using the equations of appendix A. Shown in figure 9 are the effects of these parameters on ground roll distance as they vary from sea-level standard conditions. Included are the distributions of these quantities

from standard values for the 59 XB-70 takeoffs studied. Thus, the figure shows the amount by which ground roll distances were aided or penalized by variations of each parameter for the tests. For example, the frequency-distribution bar graph in figure 9(a) indicates that 40 percent of the tests had thrust values of 8000 pounds (35,600 newtons) to 12,000 pounds (53,400 newtons) lower than standard, sea-level thrust. These variations were accounted for in the standardization. As seen, a correction of this magnitude causes the standard distance to be about 500 feet (150 meters) less than measured. Also, as shown, the ground roll distances had a dispersion of about 1500 feet (460 meters) because of thrust variations alone.

Figures 9(b) and 9(c) show the effect of temperature and ambient pressure (pressure altitude) on ground roll distance resulting from their effect on thrust. As shown, temperature was much more significant than pressure altitude; pressure-altitude variation resulted in only approximately 200 feet (60 meters) of distance change.

Figures 9(d) and 9(e) show the effect of ambient density and wind, respectively, on the measured ground roll distances. Density variations accounted for approximately 1000 feet (300 meters) variation in ground roll distance, and wind variations accounted for about 1500 feet (460 meters) dispersion.

Figures 9(f) and 9(g) show the effects of runway grade and rolling friction on XB-70 ground roll distance. Because all tests were conducted from the same relatively flat, dry runway, no frequency-distribution bar graphs are presented.

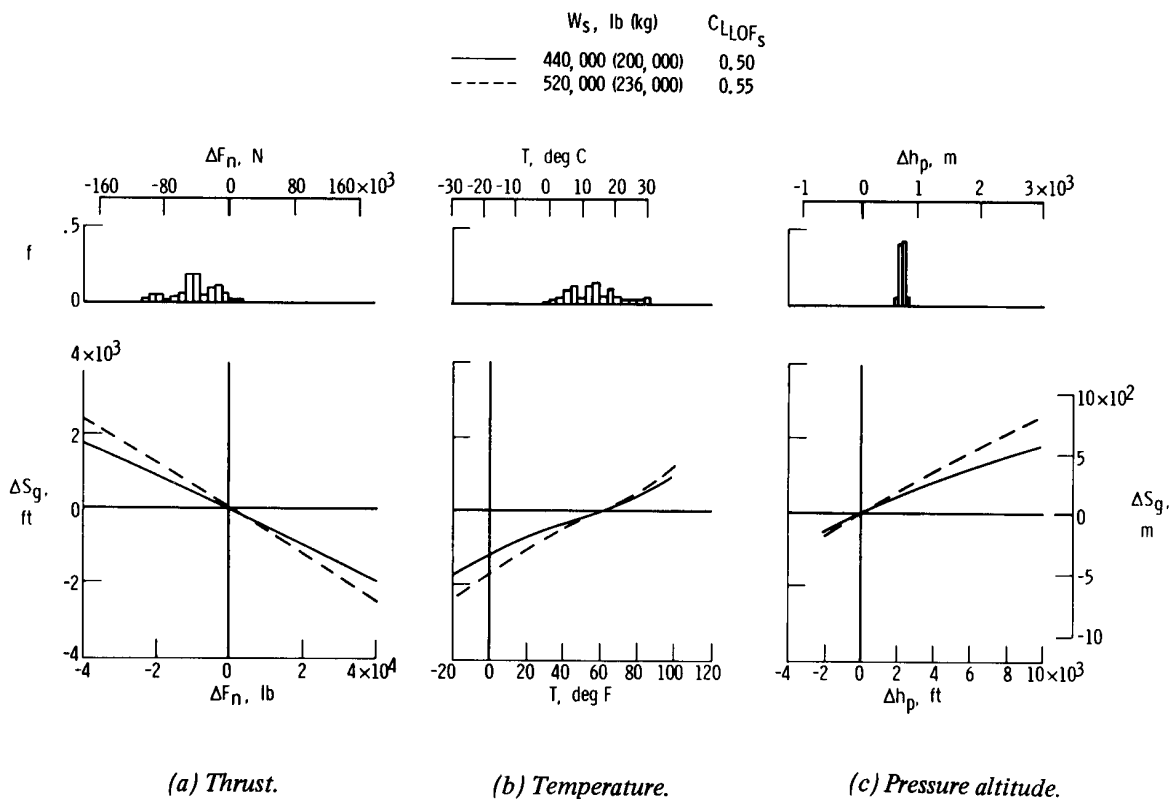


Figure 9. Effect of variation of takeoff parameters on XB-70 ground roll distance.

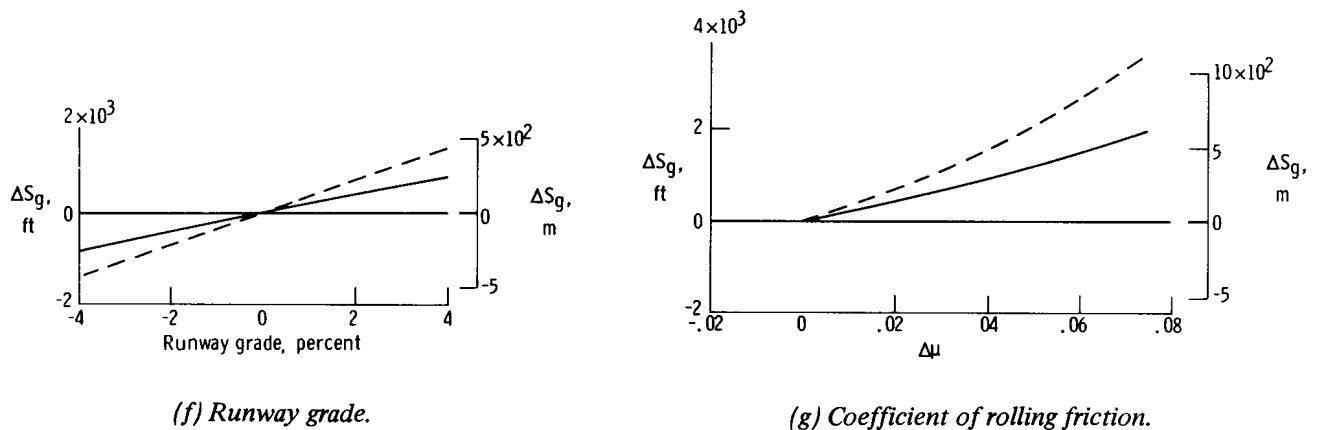
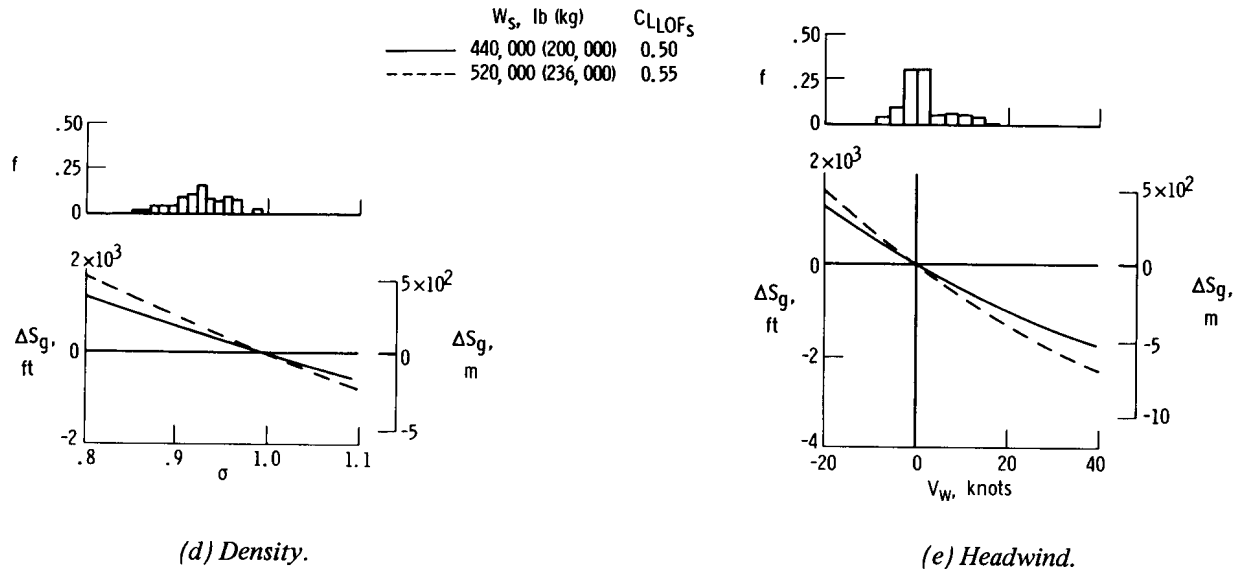


Figure 9. Concluded.

### Air-Phase and Field-Length Performance

Figure 10 presents the standardized air-phase performance in terms of distance versus specific kinetic-energy gain  $h_v$  from lift-off to a height of 35 feet (10.7 meters). Distances are standardized for ambient density, thrust, and airplane weight and are corrected to a zero-wind condition. As noted in appendix A, the standardization equation assumes that test and standard lift coefficients are the same at takeoff and at the air-phase height of 35 feet (10.7 meters). When  $h_v$  is zero, all the excess thrust is used for climbing, without any increase in speed. In this instance, the predicted minimum air-phase distance is 280 feet (85 meters) for an airplane weight of 520,000 pounds (236,000 kilograms). It should be noted that, under normal operating conditions, the air-phase distances ranged between 800 feet (240 meters) and 4000 feet (1200 meters), indicating that an accelerating climbout was preferred by the pilots.

The predicted air-phase performance curves shown in figure 10 were calculated by using equation (B5). These curves represent the average of the test lift coefficients

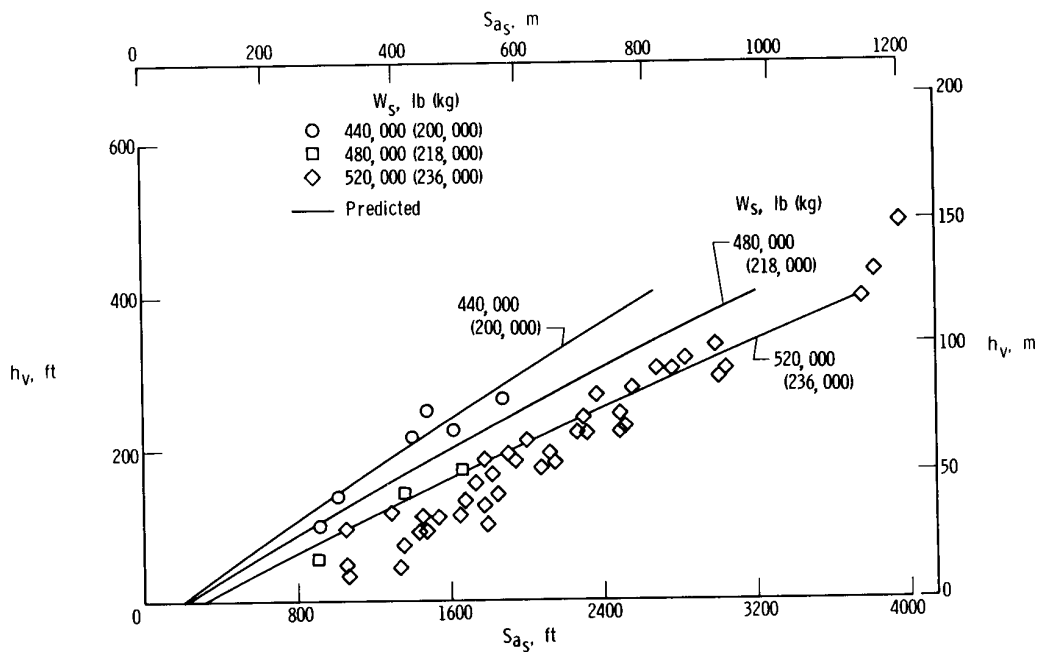


Figure 10. Variation of XB-70 air-phase distance with kinetic-energy gain during initial climb to a height of 35 feet (10.7 meters).

at lift-off. For an energy gain of less than 200 feet (60 meters), the predicted air-phase distances are shorter than indicated by the flight data, because the angle of attack after lift-off for the steeper climbouts (i. e., those associated with small  $h_v$ )

generally increases over that at lift-off. This causes higher drag and, hence, longer distances for a given energy value than when angle of attack is not increased. The larger test air-phase distances agree well with predictions because, for the more gradual climbouts, the angle of attack was generally constant after lift-off. (See fig. 2(b).)

The standardized takeoff performance is shown in figure 11 as total distance from brake release to the air-phase height. The predicted curves are for constant kinetic-energy increments  $h_v$  and an airplane weight of 520,000 pounds (236,000 kilograms).

These predicted curves are based on a constant lift coefficient. The minimum total takeoff distance to clear a 35-foot (10.7-meter) obstacle is shown. This minimum distance is a function of the minimum lift-off speed and the climb gradient as indicated by the energy gain during the climbout. The nominal operational performance, indicated as a fairing of the 520,000-pound (236,000-kilogram) test data, parallels the minimum curve. As indicated for a 200-foot (60-meter) energy gain, the nominal performance is approximately 500 feet (150 meters) longer than the predicted minimum distance. The inset in figure 11 shows the lift-off speeds required for minimum distance as a function of the energy gain  $h_v$  during the airphase. The lift-off speeds corresponding to the minimum distances for a 200-foot (60-meter)  $h_v$  are approximately 5 knots greater than the minimum lift-off speeds defined by the tail-scraper angle in figure 6.

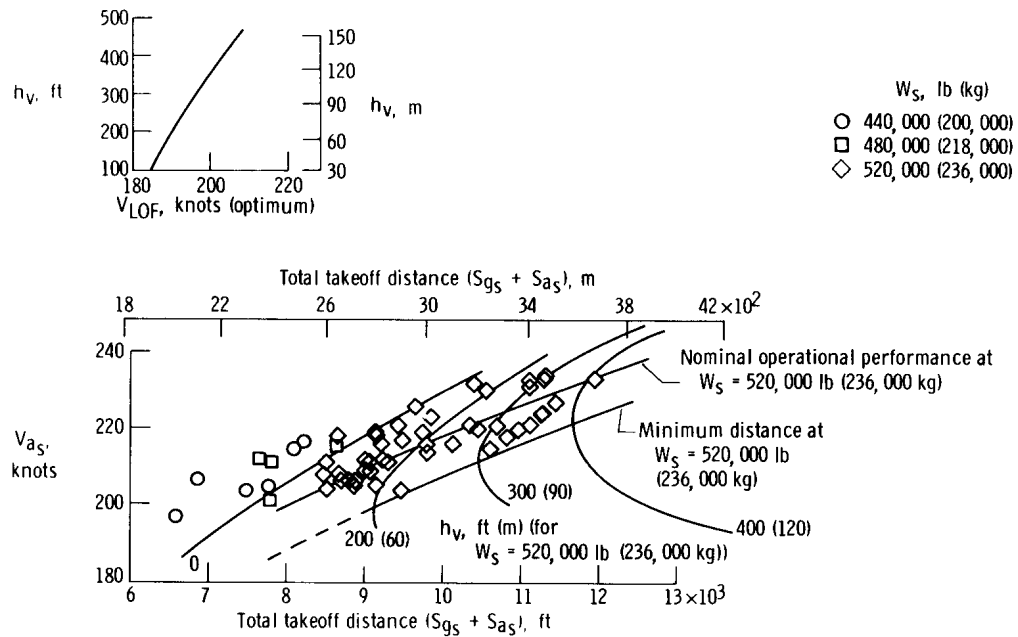
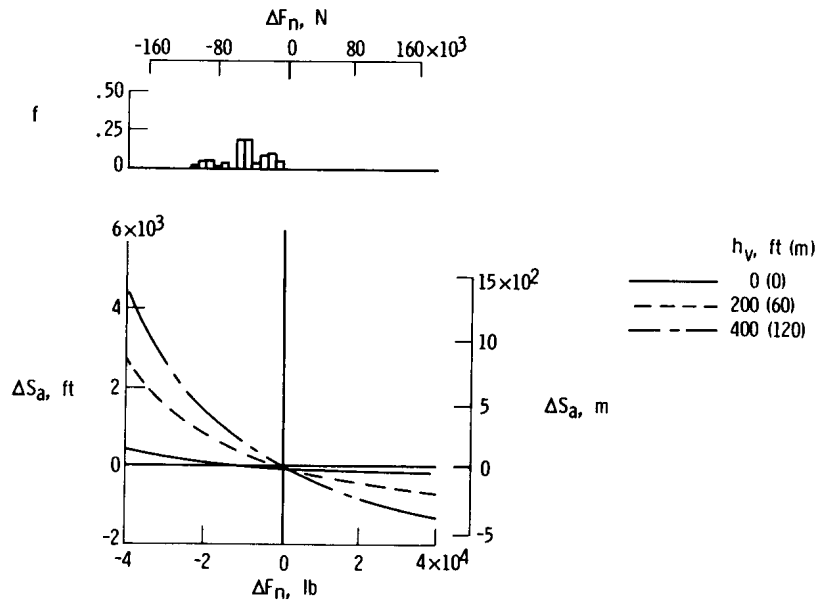


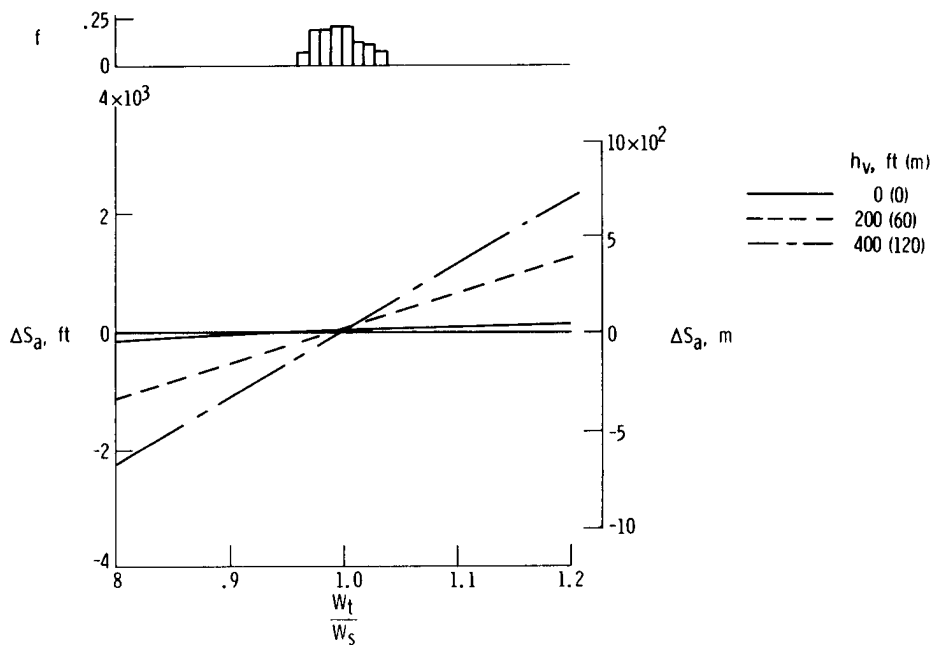
Figure 11. Variation of XB-70 takeoff distance with velocity at a height of 35 feet (10.7 meters).

Figures 12(a) to 12(c) show the effect of variations of thrust, weight, and ambient density, respectively, on air-phase distance. Also included, as in figure 9, are frequency-distribution bar graphs. As shown, for small values of  $h_v$  (i.e., minimum-distance air-phase climbouts), air-phase corrections are generally small. Of the three parameters, thrust caused the largest variation in air-phase distance; on some takeoffs a thrust deficiency increased the air-phase distance by more than 1500 feet (460 meters).

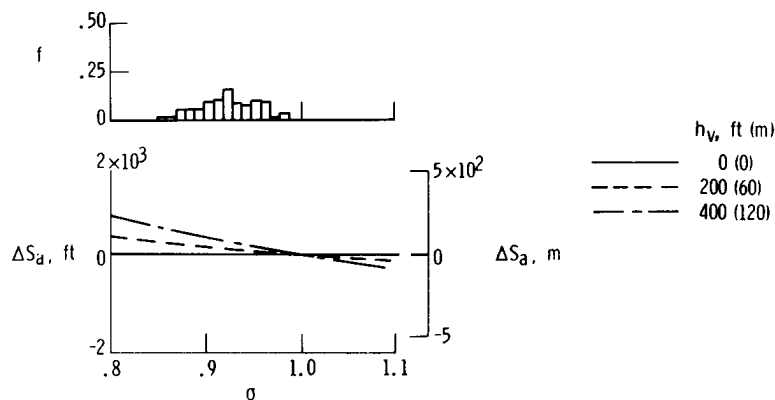


(a) Thrust.

Figure 12. Effect of variation of takeoff parameters on XB-70 air-phase distance.  $W_S = 520,000$  lb (236,000 kg).



(b) Weight.



(c) Density.

Figure 12. Concluded.

## CONCLUDING REMARKS

Analysis of takeoff performance data for the XB-70 airplane and comparison of the data with simple predictions led to the following conclusions, which may be pertinent to other supersonic aircraft of similar configurations. (All specific performance values are for a takeoff weight of 520,000 pounds (236,000 kilograms).)

Simplified performance prediction equations adequately represented the takeoff performance prior to rotation. For example, distance from brake release to initiation of rotation was determined with the variation of velocity to an accuracy of approximately 100 feet (30 meters). Refined prediction techniques need to be applied to properly account for performance during the rotation phase, which is significantly affected by varying aerodynamic drag.

Because of the significant drag at the high aircraft attitudes required for takeoff, the standardized ground roll distance for a given velocity was increased nominally by 400 feet (120 meters) over that which would occur with no increase in drag. Variations in pilot technique to rotate the aircraft caused a 300-foot (90-meter) dispersion in ground roll distance at a given velocity. The shorter duration rotations initiated 20 knots prior to lift-off were preferred because they minimized the rotation distance and were more easily executed.

Standardized performance for all engines operating during climb from lift-off to a height of 35 feet (10.7 meters) (air phase) was marginal because of low longitudinal accelerations, resulting from high induced drag at lift-off attitude. Air-phase distances varied from 800 feet (240 meters) to 4000 feet (1220 meters), depending on the climbout technique used. The nominal air-phase performance resulting from the tests was only 500 feet (150 meters) longer than for the theoretical minimum distance for any given energy gained.

The conventional methods used for standardizing takeoff distance were generally satisfactory prior to rotation; however, additional work is required to include rotation variables in standardizing test data and in more fully defining the rotation effects on performance from a limited number of takeoff tests.

Flight Research Center,  
National Aeronautics and Space Administration,  
Edwards, Calif., September 18, 1970.

## APPENDIX A

### STANDARDIZATION PROCEDURES FOR EVALUATING TAKEOFF PERFORMANCE

The analysis of takeoff data requires that the random, test-day, atmospheric conditions and pilot techniques be normalized to standard conditions. Procedures and equations for accomplishing this are presented in references 9 and 10. Interpretation and application of these procedures and equations to evaluation of the XB-70 performance are discussed in this appendix.

#### Standardization of Ground Roll Distance

Distance related to weight.— Corrections are first made to refer the test distance to zero wind, constant lift coefficient, and zero runway grade. The latter correction was not necessary for the tests of this report. Wind corrections were made by using the following equation (from refs. 9 and 10):

$$S_{g_w} = S_{gt} \left( \frac{V_{LOF} + V_w}{V_{LOF}} \right)^{1.85} \quad (A1)$$

in which the velocities  $V_{LOF}$  and  $V_w$  are measured with respect to the ground. The value of the exponent in this equation is an empirical value that corrects distance variations resulting from dependence of excess thrust on wind.

To effectively eliminate the lift-off velocity  $V_{LOF}$  as a variable for determining the relationship of ground roll distance to aircraft weight, the ground roll distance is corrected to a constant lift coefficient  $C_{L_{LOF_s}}$  by using the equation

$$S_{g_{C_L}} = S_{gt} \left( \frac{\overline{a_{x_t}}}{\overline{a_{x_{C_L}}}} \right) \left( \frac{V_{LOF_{C_L_s}}}{V_{LOF_t}} \right)^2 \quad (A2)$$

where

$$V_{LOF_{C_L_s}} = \left( \frac{W_t - F_{n_{LOF_t}} \sin \alpha_{LOF_t}}{0.5 \rho S C_{L_{LOF_s}}} \right)^{1/2} \quad (A3)$$

which results from equating aircraft weight with aerodynamic lift and vertical component of thrust at the selected value of lift coefficient  $C_{L_{LOF_s}}$ . The contribution of

the thrust term is not included in reference 9, but must be taken into account for the large thrust values of the XB-70 airplane if an error of several hundred feet in standardized distance is to be avoided. The value of  $F_{n_{LOF_t}}$  in equation (A3) was used

as 150,000 pounds (667,200 newtons), and  $\alpha_{LOF_t}$  was assigned a value of  $9.9^\circ$ ,



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corresponding to a  $C_{L_{LOF_S}}$  of 0.50, and  $10.9^\circ$ , for a  $C_{L_{LOF_S}}$  of 0.55, representing an average of the test conditions.

The term  $\frac{\overline{a_{x_t}}}{\overline{a_{x_{CL}}}}$  can vary significantly from 1 if  $a_x$  varies much with lift-off speed. However, a value of 1 was found to be satisfactory for the XB-70 performance evaluation.

After the test ground roll distance  $S_{g_t}$  is corrected to zero wind, constant  $C_{L_{LOF_S}}$ , and zero runway grade, it can be further corrected to standard weight, density, and thrust by using the equation

$$S_{g_s} = S_{g_c} \left[ \frac{\frac{W_s}{W_t} \frac{\sigma_t}{\sigma_s}}{\frac{2g}{W_t} \frac{S_{g_c}}{(V_{LOF})^2} \left( \frac{W_t}{W_s} \overline{F_s} - \overline{F_t} \right) + 1} \right] \quad (A4)$$

where  $S_{g_c}$  is the previously corrected test ground roll distance. For standardizing the distance to establish its weight dependence, the standard weight is set equal to the test weight.

For XB-70 performance evaluation, the average thrust values  $\overline{F_t}$  and  $\overline{F_s}$  were approximated by using the test values at  $V = 0.75 V_{LOF}$ , as suggested in reference 9. Because aircraft-measured thrust data were limited, the engine manufacturer's specification curves (ref. 11) were used to obtain both  $\overline{F_{gs}}$  and  $\overline{F_{gt}}$ , and these values were used in lieu of  $\overline{F_{ns}}$  and  $\overline{F_{nt}}$ . This procedure is satisfactory because the value of the quantity  $\left( \frac{W_t}{W_s} \overline{F_{gs}} - \overline{F_{gt}} \right)$  (eq. (A4)) is acceptably close to the value of  $\left( \frac{W_t}{W_s} \overline{F_{ns}} - \overline{F_{nt}} \right)$ . The adequacy of this approximation was verified during the takeoffs for which values of measured thrust were available. However, because  $F_{gs}$  values from reference 11 are larger than corresponding values of  $F_{ns}$  based on the few available thrust measurements, ground roll and air-phase standardized distance corrections based on  $\overline{F_{gs}}$  are slightly smaller than those based on  $\overline{F_{ns}}$ . The magnitude of this discrepancy is estimated to be less than 1 percent of the true distance for any of the XB-70 tests and is dependent on the values of ambient temperature and pressure used to standardize the thrust.

Distance related to velocity. — To relate ground roll distance to velocity, the ground roll distance is not corrected to maintain constant  $C_{L_{LOF}}$ , because velocity

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must be retained as a variable. Instead, the velocity is corrected by assuming that  $C_{L_{LOF}}$  is constant for the test and standard-day conditions. The required correction

is derived as follows: Assume that  $W = L$  at lift-off, then  $C_{L_{LOF_t}}$  and  $C_{L_{LOF_s}}$  can be written as

$$C_{L_{LOF_t}} = \frac{2\overline{W_t}}{\rho_t (V_{LOF_t})^2} \quad (A7)$$

$$C_{L_{LOF_s}} = \frac{2W_s}{\rho_s (V_{LOF_s})^2} \quad (A8)$$

Since the test and standard-day lift coefficients are assumed to be constant, equating equations (A7) and (A8) results in

$$\frac{2W_t}{\rho_t (V_{LOF_t})^2} = \frac{2W_s}{\rho_s (V_{LOF_s})^2} \quad (A9)$$

and

$$V_{LOF_s} = \sqrt{\frac{W_s \rho_t}{W_t \rho_s}} V_{LOF_t} \quad (A10)$$

Equation (A10), then, is the equation that is to be used for correcting lift-off velocity when equation (A4) is used for establishing the relation of  $S_{gs}$  with lift-off velocity.

To establish the XB-70 ground roll relationship to lift-off velocity, it was found best not to correct the ground roll distance to a zero-wind condition. By neglecting the effects of wind velocity on excess thrust, the effect of the wind correction is merely to shift the data points along the curves presented in figures 5 and 6. An error analysis showed that the difference in calculated ground roll distance due to the estimated change in excess thrust is considerably less than the likely error in distance due to uncertainties in the applied value of wind velocity  $V_w$ .

As indicated in the preceding discussion, equation (A4) was used directly, without any corrections to the test ground roll distance. Corrected distances were calculated for the standard weights shown in figure 5 and plotted as a function of corrected or standard velocity.

### Standardization of Air-Phase Distance

The general formula derived in reference 9 and used to standardize XB-70 air-phase distance is

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$$S_{a_s} = S_{a_t} \left[ \frac{\frac{W_s}{W_t} \frac{\sigma_t}{\sigma_s} h_v + h_a}{(h_v + h_a) + S_{a_t} \left( \frac{\overline{F_{ns}}}{W_s} - \frac{\overline{F_{nt}}}{W_t} \right)} \right] \quad (A11)$$

where  $h_a$  is the air-phase height, considered to be 35 feet (10.7 meters) for calculations in this report, and

$$h_v = \frac{V_a^2 - V_{LOF}^2}{2g} \quad (A12)$$

is the specific kinetic energy gain during the air phase. This equation assumes that test and standard lift coefficients are the same both at takeoff and at the air-phase height. It also assumes that excess thrust is constant. For the XB-70 airplane,  $\overline{F_{nt}}$  and  $\overline{F_{ns}}$  were referenced at lift-off. Small corrections to account for aircraft

drift were made to  $S_{a_t}$  by assuming that the XB-70 airplane drifted with the wind

during the air-phase period. By using this equation, air-phase performance can be conveniently expressed by a plot of  $S_{a_s}$  versus  $h_v$ . In general,  $S_{a_t}$  can be standard-

ized to a constant lift coefficient, but for the XB-70 data this correction was found to vary erratically and therefore was not made.

## APPENDIX B

### RELATIONSHIPS FOR PREDICTING TAKEOFF PERFORMANCE

The general equation for predicting takeoff ground roll distance is

$$S_g = \frac{W}{2g} \frac{V_{LOF}^2}{F_n - (D + \mu W - \mu L \cos \alpha)} \quad (B1)$$

Expanding and simplifying by using average values of the quantities rather than the time-varying functions, the equation becomes

$$S_g = \frac{\bar{W}}{2g} \frac{V_{LOF}^2}{F_n - \frac{1}{2} \rho S \bar{V}^2 (\bar{C}_D - \bar{C}_L \bar{\mu}) - \mu \bar{W}} \quad (B2)$$

Equation (B2) can be used directly to determine the relationship of  $S_{g_s}$  to  $V_{LOF_s}$  for given values of  $W_s$ . However, for determining the relationship of  $S_{g_s}$  to  $W$ , the lift-off velocity  $V_{LOF}$  can be expressed in terms of weight, thrust, and lift coefficient at lift-off as follows:

$$\left. \begin{aligned} L &= C_L \frac{1}{2} \rho V^2 S \\ W &= L + F_{n_{LOF}} \sin \alpha_{LOF} \end{aligned} \right\} \quad (B3)$$

This leads to the expression

$$V_{LOF} = \sqrt{\frac{W_{LOF} - F_{n_{LOF}} \sin \alpha_{LOF}}{\frac{1}{2} \rho S C_{L_{LOF}}}} \quad (B4)$$

Thus, by selecting standard values of  $C_{L_{LOF}}$ ,  $V_{LOF}$  can be calculated and substituted into equation (B2). Hence,  $S_g$  can be determined as a function of  $W$  for given values of  $C_{L_{LOF}}$ .

For calculations of the XB-70 performance,  $\bar{C}_D$  and  $\bar{C}_L$  were taken at  $\alpha = 0^\circ$ , appropriate to conditions prior to rotation (values were obtained from ref. 8). Hence, the calculations do not reflect rotation effects on performance. The quantity  $\bar{F}_n$  was

## APPENDIX B

determined as a function of velocity (from ref. 8) where the velocity was taken as  $0.75V_{LOF}$ .

The air-phase distance can be written in equation form as

$$S_a = \frac{W(h_v + h_a)}{\overline{F}_n - \frac{1}{2}\rho\overline{V}^2\overline{C}_{Ds}} \quad (B5)$$

where  $h_v$  is defined by equation (A12). For a given  $C_{LLOF}$ , equation (B4) can be used to calculate  $V_{LOF}$ . For a given  $h_v$ ,  $V_a$  can then be determined and, hence,  $\overline{V}$ .

For the XB-70 air-phase calculations,  $F_n$  was determined as a function of  $V$  (obtained from ref. 8). Weight was estimated to decrease by 4000 pounds (1800 kilograms) from brake release to lift-off. The curves shown in figure 10 represent averages of values calculated for  $C_{LLOF}$  values of 0.50 and 0.55.

The following table lists the values of the required quantities used to calculate the predicted performance curves shown in figures 4(b), 5, 6, 10, and 11:

Quantity	Value	Source
Ground roll performance		
$\overline{C}_{LLOF}$ , trimmed in ground effect	0.55	Reference 8
$\overline{C}_D$ , trimmed in ground effect (estimated)	0.0225	Reference 8
$\overline{F}_n$	Variable with $\overline{V}$	Reference 8
$F_{nLOF}$	150,000 lb (667,200 N)	Reference 8
$\alpha_{LOF}$	$\begin{cases} 9.9^\circ \text{ for } C_L = 0.50 \\ 10.9^\circ \text{ for } C_L = 0.55 \end{cases}$	Reference 8
$\mu$	0.025	
$\rho$	0.002377 slugs/ft <sup>3</sup> (1.225 kg/m <sup>3</sup> )	Standard sea level
$g$	32.17 ft/sec <sup>2</sup> (9.8 m/sec <sup>2</sup> )	Standard sea level
Air-phase performance		
$C_{LLOFs}$	0.50, 0.55	
$\overline{C}_D$ , trimmed in ground effect	$\begin{cases} 0.085 \text{ for } C_L = 0.50 \\ 0.103 \text{ for } C_L = 0.55 \end{cases}$	Reference 8
$\overline{F}_n$	Variable with velocity	Reference 8
$\rho$	0.002377 slugs/ft <sup>3</sup> (1.225 kg/m <sup>3</sup> )	Standard sea level

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